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Performance Evaluation of the SPT–140

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As part of an on-going cooperative program with industry, an engineering model SPT-140 Hall thruster which may be suitable for orbit insertion and station-keeping of geosynchronous communication satellites was evaluated with respect to thrust and radiated electromagnetic interference at the NASA Lewis Research Center. Performance measurements were made using a laboratory model propellant feed system and commercial power supplies. The engine was operated in a space simulation chamber capable of providing background pressures of $4x10^{-6}$ Torr or less during thruster operation. Thrust was measured at input powers ranging from 1.5 to 5 kilowatts with two different output filter configurations. The broadband electromagnetic emission spectra generated by the engine was also measured for a range of frequencies from 0.01 to 18000 Mhz. These results are compared to the noise threshold of the measurement system and MIL-STD-461C where appropriate.

Introduction

Based on the state of readiness of the technology, electric propulsion has begun to be considered for widespread application on both commercial and government spacecraft.[1,2] In order to meet future spacecraft propulsion requirements, more advanced electric propulsion technologies are currently under development. An example of this is the current efforts to develop Hall effect thrusters capable of operating at the higher powers anticipated for future spacecraft. Systems up to ten kilowatts may be suitable for a number of propulsion functions including, but not limited to, orbit insertion, station-keeping, reposition, collision avoidance, and deorbit.[2]

This report is a status of the evaluation of an SPT-140 Hall thruster conducted at NASA's Lewis Research Center (LeRC) through a cooperative program with Space Systems/Loral. Initial testing of this engine under a similar cooperative program was reported previously.[3]

The engine evaluated was manufactured by Fakel Enterprises in Kaliningrad, Russia and provided for test by International Space Technology, Inc. (ISTI). The objective of these evaluations were to verify the performance of the engine with two different electrical output filter configurations and to evaluate the performance of this engine for a power limited application. Additionally the radiated electromagnetic radiated interference generated by operation of the engine was evaluated as has been previously done for other various electric propulsion devices.

Apparatus and Procedure

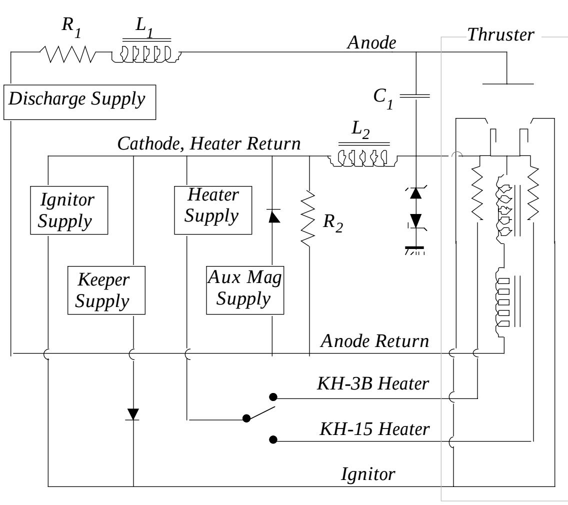
Three different tests were conducted with the SPT-140: an assessment of the performance of the engine at operating points previously tested using two different electrical output filters, an assessment of the performance of this engine at a constant 3.4 kilowatt input power, and an assessment of the broadband radiated emissions generated by the thruster during operation. The engineering model SPT-140 used in these tests is shown in Figure 1. The thruster was operated at powers between 1.5 and 5 kilowatts. This was accomplished by providing anode xenon flow

Figure 1: Picture of the SPT-140. The KH-15 cathode is on the left.

rates ranging from 5 to 20 mg/s at discharge voltages between 250 and 400 volts. Although two cathodes were available for use on this thruster only one, designated the KH-15, was used during the testing. Current levels ranged between 5 and 23 amperes. The KH-15 cathode had a lanthanum hexaboride emitter which was preheated with a resistive heater prior to operation.

The thrust produced by the SPT-140 was measured using an inverted pendulum design thrust stand which has been used in previous evaluations of Hall thrusters.[4,5] The thrust stand was calibrated in-situ using three weights with a mass of approximately 0.010 kilograms each. The uncertainty in the thrust measurements, primarily due to zero drift, was estimated to be ±1.5%. Measurements were taken in a large space simulation chamber (Tank 5) with a xenon pumping speed in excess of 500,000 liters per second. The dimensions of Tank 5, which is cylindrical, are 19m in length by 5m in diameter. The background pressures were between 2 and $4x10^{-6}$ Torr of xenon during thruster operation.

A schematic of the electrical configuration used is shown in Figure 2. Commercially available power supplies were used to run the discharge, cathode heater, magnets, cathode ignitor and cathode keeper. The discharge supply was a constant voltage source with an in-line ballast resistor. Because Hall thrusters power systems typically include an output filter to minimize the effects of potential current oscillations on the various power supplies, the configuration of this filter is included in the electrical schematic. For these tests two different output filter configurations were used. The only significant difference between the two configurations



R_1 = 0-30 Ω, R_2 = 1-6 Ω, C_1 = 20 or 100 μF, $L_1 = L_1$ = 350 mH

Figure 2: Electrical schematic for SPT-140 testing.

was the magnitude of the capacitor between the anode and cathode. The value of this capacitor was either 20 or 100 microfarads. No investigation was undertaken to optimize the configuration of this output filter.

The thruster electromagnets were connected in series with the thruster discharge. The entire electrical system was allowed to float relative to ground with the exception of the cathode. The cathode was clamped to within 50 volts of facility ground by zener diodes to limit voltage excursions during start-up.

The thruster was operated on commercially available research grade xenon (purity better than 99.9995%). A laboratory model feed system which incorporated commercially available mass flow controllers was used to provide the desired flow rate to the anode and cathode. These flow meters were calibrated before and after each series of tests. Uncertainties in mass flow rate measurements were estimated to be ±2%.

Broadband radiated electromagnetic emissions were measured in a frequency range from 0.01 to 18,000 Mhz with the thruster running at a discharge current of 12.5 amperes and a discharge voltage of 300 volts. The capacitor between the cathode and anode in the electrical output filter was 100 microfarads for the EMI tests. The apparatus used for the EMI measurements is described in detail elsewhere.[6] Only broadband emissions were measured since the SPT-140 can be considered a broadband source. A suite of antennas including passive rods, biconical, broadband dipole, and big log periodic dipole types were located at a distance of 1 meter from the engine in an arc behind the thruster. The antennas were contained within a kapton tent to minimize any potential plasma effects. The noise threshold for the measurement system was measured and compared to the radiated emissions.

Results and Discussions

As previously mentioned, in order to more completely evaluate the operational characteristics of the SPT-140 thruster, three different tests were conducted: an assessment of the performance of the engine at operating points previously tested using two different electrical output filters, an assessment of the performance of this engine at a constant 3.4 kilowatt input power, and an assessment of the broadband radiated emissions generated by the thruster during operation. All the performance data taken in the course of testing, including the background pressure for each data point, are presented in tabular form in the Appendix. Cathode to ground voltages which are not included in these data were on the order of -20 volts.

General performance assessment:
Figure 3 depicts the variation of specific impulse with thrust from this investigation and for data taken in the same facility with the same engine during a previous investigation. The figure shows good agreement with the exception of the lower specific impulse points at about 200 mN of thrust. These data were taken at a constant 3.4 kW input power and will discussed in more detail subsequently.

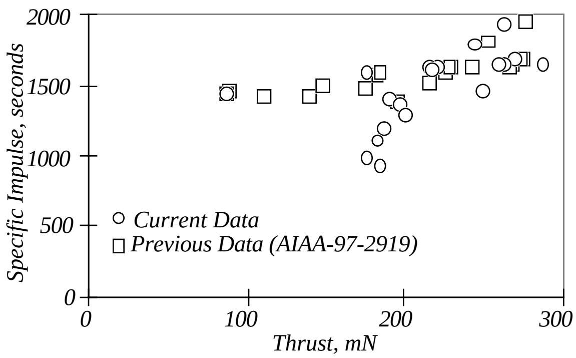


Figure 3: Specific Impulse versus thrust.

Both output filters were used for these measurements with no appreciable effect on performance or the magnitude of the voltage and current fluctuations on the discharge power supply side of the output filter. All measurements were taken at background pressures of 4 x10^{-6} Torr of less so the effect of facility pressure on performance previously reported[3] was minimal. No attempt was made to optimize the performance at any operating point with regard to the magnetic field strength which was adjustable through the use of an auxiliary power supply.

Constant Power Assessment:
Because the SPT-140 is capable of operating over a range of discharge voltages and currents it is possible to operate the thruster in various configurations at a constant thruster power. This allows for the possibility of selecting the most desirable thrust, efficiency, or specific impulse at a given thruster power. During this investigation the performance of the SPT-140 was evaluated at a constant input power of 3.4 kilowatts. High discharge voltages have been shown to result in higher specific impulses and the high discharge currents associated with low discharge voltage operation were thought to result in higher thrust. This increase in thrust is predicated on the fact that the anode flow rate and the discharge current are linearly proportional and, that the exit velocity is proportional to the square of the applied voltage, ie:

$$\text{Thrust} \propto \text{anode flow rate or discharge current}$$

and

$$\text{Thrust} \propto [\text{discharge voltage}]^{0.5}$$

therefore, based on these assumptions, for a constant power (discharge voltage x discharge current = constant)

$$\text{Thrust} \propto [\text{discharge voltage}]^{-0.5}$$

These assumptions were investigated by reducing the discharge voltage in several steps from 240 volts to 150 volts while keeping the input power constant. The results are shown in Figure 4 along with the corresponding points calculated based on the 240 Volt point assuming the previously stated relationships held true.

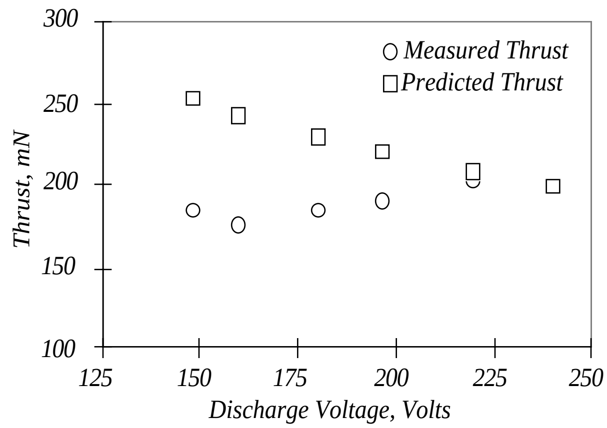


Figure 4: Discharge current versus anode flow rate.

While the thrust did increase as the voltage was dropped from 240 volts to 200 volts, all data points taken at lower discharge voltages had measured thrusts less than that measured at a discharge voltage of 200 volts. No attempt was made to optimize the magnetic field strength for any of these points. This suggested that the previous assumptions regarding the functional dependence of anode mass flow rate with respect to current and thrust with respect to discharge voltage were not valid.

As shown in Figure 5 the discharge current did vary linearly with anode mass flow rate up to approximately 15 amperes. At discharge currents above 15 amperes it took a correspondingly smaller increase in anode flow rate to effect a given change in discharge current than at lower currents. Data previously taken at currents below 15 amperes are also included to show repeatability.

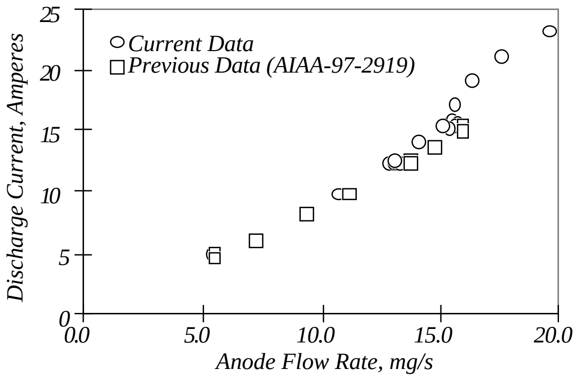


Figure 5: Discharge current versus anode flow rate

As a result of the more rapid increase in discharge current with anode flow rate at discharge currents above 15 amperes, the thrust did not increase in the manner expected at these currents. This phenomena remains unexplained and as yet has not been duplicated in subsequent tests. On possible explanation is that the provided magnetic field strength was so far from the optimal value that the axial electron plasma conductivity was higher at these discharge higher currents. This was beyond the scope of this investigation and was not pursued.

Subsequent data taken by Fakel has demonstrated higher performance at a constant 3.4 kilowatts than measured during this investigation with a near linear
variation of discharge current with anode flow rate at currents up to 22 amperes. That was accomplished by running the external and internal electromagnets separately and optimizing them for the low voltage operating points. These data have been tabulated and are shown in the Appendix.

Broadband Emission Spectrum:
The measured broadband radiated emissions from the SPT-140 are shown for three separate frequency ranges in Figures 6a,6b, and 6c. Also shown in these figures are the noise threshold of the measurement system and MIL-STD-461C were appropriate. It should be noted that scale for the emission level axis on each of the three figures is different. Both the noise floor and the emission spectra exceed MIL-STD-461C for frequencies up to 0.1 Mhz. Both the noise threshold and the radiated emissions drop to a low of about 30dBμV/m/MHz. In general there are not substantial broadband emissions above 100 Mhz. Because of the difficulty in measuring emission spectra from a source of this type in a metallic chamber these data should primarily be used for comparison purposes and should not be taken as the absolute source strength without some additional analysis.

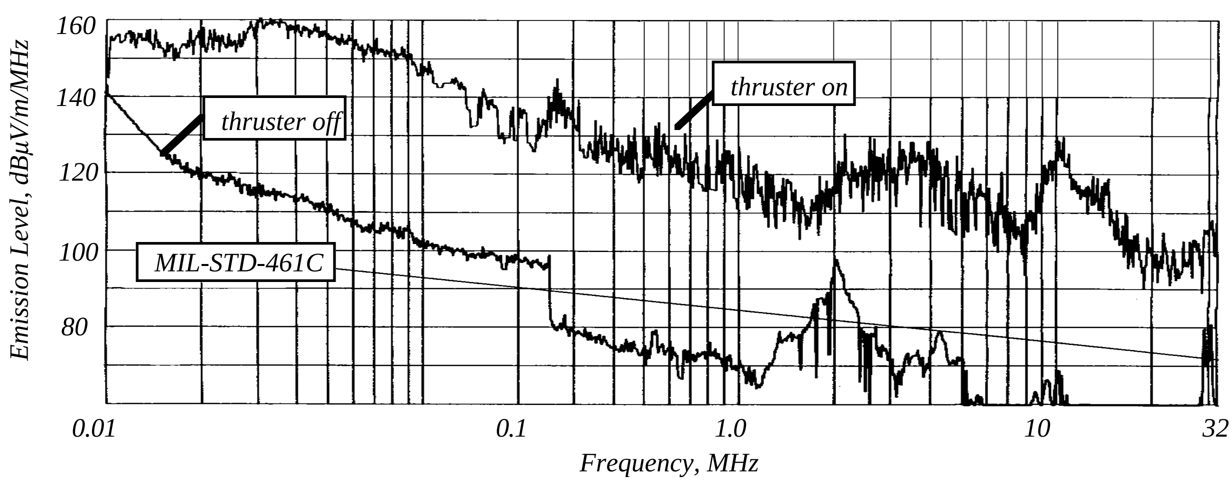


Figure 6a: Broadband background emission and radiated emission from the SPT-140 operating at 300 volts and 12.5 amperes over a frequency range of 0.01 to 32 Mhz.

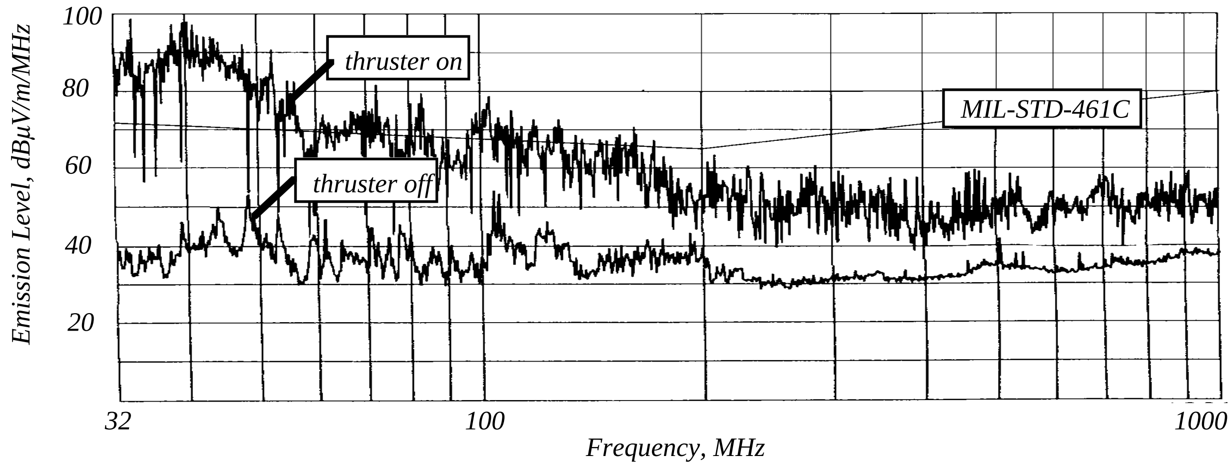


Figure 6b: Broadband background emission and radiated emission from the SPT-140 operating at 300 volts and 12.5 amperes over a frequency range of 32 to 1000 MHz.

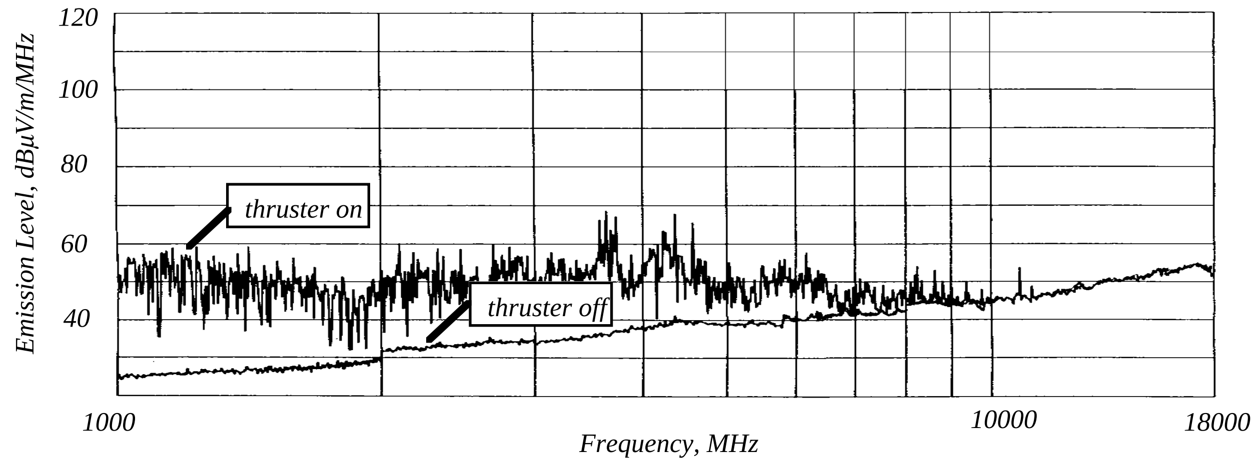


Figure 6c: Broadband background emission and radiated emission from the SPT-140 operating at 300 volts and 12.5 amperes over a frequency range of 1000 to 18000 MHz.

Conclusions

Thrust over a range of operating conditions, performance at a fixed input power, and broadband radiated emissions were measured for an engineering model SPT-140 Hall thruster under a cooperative SS/L/NASA LeRC program. These measurements all indicated the suitability of this engine for various spacecraft applications. The performance measurements were made using a laboratory model propellant feed system and commercial power supplies while the engine was operated in a space simulation chamber capable of providing background pressures of $4x10^{-6}$ Torr or less. The effect of varying the capacitor size between the anode and cathode within the electrical output filter was found to be negligible over a range of input powers from 1.5 to 5 kilowatts. The broadband electromagnetic emission spectra generated by the engine measured for a range of frequencies from 0.01 to 18000 Mhz showed emissions in excess of MIL-STD-461C at frequencies below 100 Mhz. The emissions at frequencies above this value were below MIL-STD-461C and approached the minimum detectable values at frequencies in excess of 1000 MHz.

Acknowledgment

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Appendix

Table 1: Experimental Data taken at LeRC during this investigation

anode flow	cathode flow	total flow	current	voltage	aux mag current	Power	Thrust	Isp	efficiency	Tank P
mg/s	mg/s	mg/s	amperes	volts	amperes	Watts	mN	sec		Torr
15.5	2.0	17.5	15.4	250	0	3850	251	1464	0.47	3.8E-06
15.5	2.0	17.5	15.4	250	0	3850	251	1464	0.47	3.8E-06
15.5	2.0	17.5	15.7	248	0	3894	251	1464	0.46	3.8E-06
15.5	2.0	17.5	16	246	2	3937	251	1461	0.46	3.8E-06
15.8	2.0	17.8	15.4	298	0	4589	287	1647	0.50	3.8E-06
15.8	0.7	16.5	15.4	300	0	4620	270	1670	0.48	3.5E-06
15.7	0.7	16.4	15.3	298	3	4561	264	1645	0.47	3.5E-06
13.2	0.7	13.9	12.5	300	3	3752	221	1617	0.47	3.0E-06
12.9	0.7	13.6	12.5	300	0	3750	215	1614	0.45	2.9E-06
13.2	0.7	13.9	12.5	300	5	3758	217	1597	0.45	3.0E-06
13.2	0.7	13.9	12.5	399	2	4989	263	1929	0.50	3.0E-06
13.3	0.7	14.0	12.46	351	2	4375	246	1790	0.49	3.0E-06
13.1	0.7	13.8	12.51	251	2	3142	191	1409	0.42	3.0E-06
15.4	0.7	16.2	15	300	2	4502	260	1641	0.46	3.5E-06
10.7	0.7	11.4	10.02	300	2	3008	177	1579	0.46	2.5E-06
5.4	0.7	6.1	5.04	300	2	1514	87	1449	0.41	1.3E-06
14.0	0.7	14.7	14	240	0	3360	198	1371	0.40	3.2E-06
15.0	0.7	15.8	15.35	220	0	3377	201	1302	0.38	3.4E-06
15.6	0.7	16.3	17.25	197.2	0	3402	189	1181	0.32	3.5E-06
16.4	0.7	17.1	19.2	180.2	-1	3460	184	1099	0.29	3.7E-06
17.5	0.7	18.2	21.1	160	-1	3376	175	979	0.25	3.9E-06
19.7	0.7	20.4	23.2	148.4	-1	3446	185	925	0.24	4.4E-06

Table 2: Experimental Data taken at Fakel with separate inner and outer magnet control.

anode flow	cathode flow	total flow	current	voltage	Inner mag current	Outer mag current	Power	Thrust	Isp	efficiency	Tank P
mg/s	mg/s	mg/s	amperes	volts	amperes	amperes	Watts	mN	sec		Torr
10.4	0.7	11.1	10	340	11	11	3400	187	1717	0.46	6.1E-05
16.8	0.7	17.5	17	200	17	13.5	3400	239	1392	0.48	8.9E-05
19.1	0.7	19.8	20	170	17	13.5	3400	242	1246	0.43	1.0E-05
21.0	0.7	21.7	21.9	155	17	13.5	3395	246	1156	0.41	1.1E-05

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13. ABSTRACT ***(Maximum 200 words)***

As part of an on-going cooperative program with industry, an engineering model SPT-140 Hall thruster which may be suitable for orbit insertion and station-keeping of geosynchronous communication satellites was evaluated with respect to thrust and radiated electromagnetic interference at the NASA Lewis Research Center. Performance measurements were made using a laboratory model propellant feed system and commercial power supplies. The engine was operated in a space simulation chamber capable of providing background pressures of 4×10^{-6} Torr or less during thruster operation. Thrust was measured at input powers ranging from 1.5 to 5 kilowatts with two different output filter configurations. The broadband electromagnetic emission spectra generated by the engine was also measured for a range of frequencies from 0.01 to 18000 Mhz. These results are compared to the noise threshold of the measurement system and MIL-STD-461C where appropriate.

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